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TRANSITION BETWEEN LAMINAR AND TURBULENT FLOW BY TRANSVERSE CONTAMINATION

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SUMMARY

Tests carried out on a flat plate in a low-turbulence constant-pressure tunnel at GALCIT showed that the transition between laminar and turbulent flow could be caused in a normally laminar region by a process of "transverse contamination" in that transition, started at some point in a normally laminar layer by an external disturbance, affected the adjacent laminar boundary layer and spread laterally as the flow progressed downstream. This lateral spread took place at an approximately constant rate, which varied slowly with the velocity of the main flow but which, once transition started, was independent of the originating cause.

INTRODUCTION

The concept of boundary-layer transition is a very complex one and still lacks a clear theoretical exposition. The only way of attacking this problem scientifically is by an experimental separation and investigation of stream conditions affecting (or probably affecting) the transition of the boundary layer from the laminar to the turbulent state. The principal conditions known to affect the transition point are:

1. The turbulence of the flow outside the boundary layer, for example, the turbulence characteristics of the wind tunnel in which the investigation is carried out

2. The pressure gradient along the boundary surface.

3. The curvature of the boundary surface.

In the series of researches on this problem, sponsored by, and conducted with financial assistance from the National Advisory Committee for Aeronautics, each of these three principal effects is supposed to be separately investigated. The part under investigation at the GALCIT is the effect of curvature on boundary-layer transition. The difficulty of this investigation is clear, when it is remembered that, in order to obtain well-defined conditions, the influence of the two other effects must be reduced to a minimum.

This research first seemed to promise excellent results, but the problem turned out to be even more complicated than had been assumed. It was necessary to investigate, improve, and even partly to develop an experimental procedure different from the one previously used. For this reason, during the latter half of 1938 and all of 1939 a research on the boundary-layer transition along a flat plate was carried out in a small wind tunnel of low-turbulence level. The investigation yielded interesting results that undoubtedly have an important bearing on the general aspects of the transition problem. Although much of this material was presented in the paper "Transition by Transverse Contamination" on January 25, 1940, at the Eighth Annual Meeting of the Institute of the Aeronautical Sciences, it is herein published for the first time.

Since the completion of the original text of this paper, further studies of the subject have been made at GALCIT. Observations concerning the results of the recent studies are given in the appendix, which was written by Dr. H. W. Liepmann.

The author wishes to express his thanks to the National Advisory Committee for Aeronautics for the grant under which this project was carried out. Also, he wishes to thank Dr. Theodor von Kármán and Dr. Clark B. Millikan for their inspiration, encouragement, and advice, without which the carrying on of this project would have been difficult indeed.

APPARATUS

The original experiments were made in the wind tunnel described in reference 1. Technical difficulties encountered in this wind tunnel made it desirable to repeat transition determinations under more carefully controlled conditions. The experiments reported herein were carried out on a stiff boundary plate centrally mounted in the working section of a small tunnel used at the laboratory for turbulence-correlation investigations. The flow in this tunnel is steady, uniform, and of very low turbulence, the isotropy of the turbulence being insured by a fine-grained honeycomb placed in the entrance. A glass plate of the finest plate glass obtainable was used as the boundary surface. The leading edge of th plate was carefully sharpened. The inclination of the plate could be slightly adjusted and the tunnel walls could be moved in and out to give any desired pressure gradient.

The technique for determining transition was essentially that of Professor B. M. Jones, wherein a small, flat, total-head tube pressed against the boundary surface is moved in a streamwise direction along the boundary. A special carriage riding on the glass plate itself was built for carrying the measuring instruments and held them at a constant perpendicular distance from the surface during a survey. The surveys were made by mounting the instrument on the carriage at the desired distance from the surface and moving the carriage along the surface by an external track mechanism. The carriage carried a fixed Prandtl pitot-static tube placed in the free stream so that the pressure of the total-head tube in the boundary layer could be balanced against the static pressure of the stream and a direct measure of the dynamic pressure throughout the boundary layer be obtained. With the total-head tube pressed against the surface the dynamic pressure had a low value in the laminar boundary layer decreasing with increasing distance downstream. At a certain distance from the leading edge the dynamic pressure suddenly increased over a very narrow region, indicating a very definitely located transition to the turbulent regime. Beyond this region the dynamic pressure again decreased with increasing distance downstream. Such a behavior of the dynamic pressure at the wall is in complete agreement with the findings of other investigators; also, since the pressure at the wall is directly proportional to the shear stress, our results are in agreement with theory.

RESEARCH PROCEDURE AND RESULTS

The usual preliminary adjustment of apparatus was made in order to control the state of the flow. The incidence of the plate was changed until a Reynolds number of transition of 1,800,000 (based on the free-stream velocity and the distance from the leading edge to the transition) indicated that a stable angle had been reached. The width of the working section was adjusted until the static pressure was constant to within 1/4 percent of the free-stream dynamic pressure over the length of the section. Transition surveys were carried out showing the dependence of transition on pressure gradient. The accuracy of adjustment was considered satisfactory because it was found that pressure gradients of the order of magnitude of 1/4 percent or less had no effect on the transition. All the preliminary adjustments were carried out at a single speed, close to the maximum obtainable in the tunnel. When these surveys were finished, determinations of transition were made at a series of speeds to test the similarity law. (See figs. 1 and 2.) The results definitely showed that the similarity law did not hold under the conditions of flow present in the tunnel. This result was a serious discrepancy from the predictions of the theory.

The pressure surveys indicated that transition tends to take place at a fixed distance downstream rather than at a fixed Reynolds number. This result gave a clue to the actual state of affairs in the boundary layer. It is well known that properties of the fluid which are carried by a turbulent transport mechanism diffuse at an angle that is relatively independent of the speed. Thus, if a disturbance on the top and the bottom of the tunnel started transition spreading across the surface, the transition region would have a V-shape, the angle of the V would change only slowly with speed, and transition along any particular line would stay approximately fixed in location.

The surveys up to this time had been confined to the center line of the glass plate. A survey was now made over the entire surface of the plate and, as predicted, the transition region was found to be V-shape. (See fig. 3.) The mouth of the V coincided closely with the leading edge of the plate and its apex lay on the center line. Surveys over a range of speeds showed that the angle and the location of the V changed but little, thus accounting for the failure of the similarity law to apply in this case. An inspection of the tunnel disclosed that the joint between the contracting section and the working section had not been carefully made; there was a misalinement of nearly 1/8 inch on both the top and the bottom. This misalinement created a very turbulent disturbance on these surfaces, and this disturbance flowing past the edges of the glass plate might easily have "contaminated" the normal laminar layer and started transition spreading across this layer. Other causes of the V-shape transition region were possible and these causes were eliminated before study was made of conditions at the misalinement of the entrance.

One possible cause existed in the great sensitivity of transition to the inclination of the plate to the air stream. The flow in the tunnel had not been carefully investigated over the entire cross section prior to this research, and it was possible that a nonuniformity in its direction existed which would put the center of the plate at a stable incidence and its edges at an unstable incidence. Such a state of flow could be caused by a double-vortex system. The axis of the vortices would be parallel to the direction of flow; one vortex would be situated in the upper half of the tunnel, the other vortex in the lower half, and they would rotate in opposite directions in accordance with the Helmholz law. Such a vortex pair would incline the flow one way at the center and the other way at the top and the bottom with a gradual change of inclination from one to the other just as is required.

Any change in the direction of flow would appear as a static-pressure gradient due to the centrifugal forces involved; an extensive survey of the static pressure in the forward part of the working section was therefore carried out. This survey revealed static-pressure gradients that might have been due either to a double-vortex system or to changes in cross-sectional shape caused by the mounting strips on the top and the bottom. If the gradients are caused by vortices, it is possible to compute their strength and the resulting inclinations of flow from the pressure surveys. Computations showed that these vortices would be sufficiently strong to cause a change in inclination of at least 15° from the center to the edge. A careful investigation of the flow direction with a fine streamer showed no such change. In fact, as far as could be detected by the streamer (the method is good to a few degrees), the flow over the entire working section was uniformly parallel. This contradiction eliminated the possibility that a double-vortex system was present.

Another possible cause of the V-shape transition region existed in the fact that the boundary layers on the top and the bottom were in a very disturbed state, for it was conceivable that their thickness increased as rapidly as the spread of transition. In this case the line of transition would merely be the line of demarcation on the glass plate of the two boundary layers. Surveys were made in planes parallel to the plate and spaced at different distances for the purpose of locating the outer edge of the boundary layer. These surveys are combined in the form of a composite diagram (fig. 4) containing all the superimposed maps for the separate planes. The technique for locating the limit of the boundary layer was simple. The total pressure everywhere in the free stream was constant but, immediately at the entrance to the boundary layer, the total pressure started decreasing owing to the dissipation of energy by the shearing forces. This knowledge was utilized to find the limit of the boundary layer by mounting a total-head tube a known distance from the surface and moving it backward along the plate until its reading started to decrease. In order to be more definite, the tube was brought to that point where the velocity was $99\frac{1}{2}$ percent of the free-stream velocity.

This survey eliminated the possibility that the V-shape transition was merely the line of demarcation of two boundary layers. As far downstream as 100 inches, the boundary layer in the center is only $2\frac{1}{2}$ inches thick and, as close as 1 inch from the plate, the boundary layer on the mounting strip at 50 inches, the distance of the apex of the V, is only $1\frac{1}{2}$ inches thick. The joining together of the 1-inch lines farther downstream and the location of the 1/2-inch line is due to the sudden rate of thickening of the boundary layer on the glass plate after transition.

With those two possibilities eliminated, it was felt desirable to investigate in greater detail the behavior of the flow in the boundary layer.

First, the thickness of the boundary layer was measured over the entire surface of the plate. The results are presented in the form of a contour map giving lines of constant boundary-layer thickness. (See fig. 5.) In the main, this map merely confirms the surveys on the location of transition. It does show that, insofar as thickness is concerned, the laminar portion of the boundary layer within the limits of the V is unaffected by the state of transition at its edges. The presence of an undisturbed region within the V is the result that would be expected from the assumption that transition is propagated laterally by a turbulent-diffusion process.

Second, an extensive three-dimensional survey of turbulence was made over the length, the breadth, and the depth of the boundary layer. Unfortunately, owing to a reconstruction of apparatus, these measurements are not so reliable as the other experimental data presented in this paper. For purposes of comparison the turbulence surveys should be satisfactory, but, as far as absolute level of turbulence in concerned, they are questionable. One survey of turbulence has been made before the reconstruction was started and, by comparison with the later measurements, a fair estimate could be made of the actual magnitude of the turbulence. (See fig. 6.) The survey along a line 2 inches above the center line shows the typical behavior of turbulence within the boundary layer at different distances from the surface. (See fig. 7.)

The characteristics of the portion of the boundary layer very close to the surface were of particular interest. If the transverse contamination is carried by the boundary-layer turbulence, a given rate of transport will require a given magnitude of turbulence to support it. It is assumed that the turbulence is isotropic and that the cross-stream component is entirely responsible for the lateral spread of transition. On this assumption the root-mean-square of the velocity fluctuations (either u' or v' as isotropy is assumed) divided by the local velocity at the point in question is equal to the tangent of the angle of spread. As the turbulence is defined as the root-mean-square of the velocity fluctuations divided by the local velocity, the boundary-layer turbulence in a critical lamina will be equal to the tangent of the angle of spread. The observed spread of $9\frac{1}{2}^{\circ}$ would require 17-percent turbulence. In planes very close to the surface where the turbulence is greater than the required 17 percent, the turbulence from the transition should spread faster than the transition itself. The uncertainty in the measurements of the absolute magnitude of the turbulence combined with the fact that the level of turbulence in the laminar boundary layer is not steady makes the results seem uncertain in this regard. The turbulence contours show the tendency for the turbulence to diffuse more rapidly than the transition, however, and they are significant because they show levels in the boundary layer with sufficient turbulence to carry out the lateral transport of transition at the observed rate.

In view of the good agreement between the transition, the boundary-layer thickness, and the turbulence surveys, it was thought advisable to put the hypothesis of transverse contamination to a more rigorous test. If it is assumed that this lateral contamination is a self-sufficient process depending on an outside disturbance only for a start, a critical test would be to change the nature of the originating disturbance and then to observe the behavior of the transition.

First, an attempt was made to eliminate the disturbance insofar as possible by placing a false top a short distance down from the real top of the test section. (See fig. 8.) This false top was merely a thin flat plate with a sharpened leading edge mounted perpendicularly to the glass plate. Unfortunately, this attempt was unsuccessful; for some unknown reason the presence of the false top caused the flow at the leading edge of the false top to be inclined sharply downward, a condition that started a turbulent layer almost immediately on its under surface and thus caused a disturbance along the edge of the glass plate as severe as the disturbance from the real top. The false top was moved from its initial position 2 inches below the real top to a 4-inch position, and finally to the center of the channel, in an attempt to get away from this flow inclination, but without success. Although this test did not give the expected results, it is significant in that in all three locations of the false top the transition region is V-shape in the same way as before except that the V is smaller in size.

The originating disturbance not having been eliminated, the test was carried to the opposite extreme, that of adding an additional disturbance. This additional disturbance was added in the center of the plate close to its leading edge in the form of the wake from a small obstacle. The obstacle was mounted perpendicularly to the surface and extended across the tunnel. A similar obstacle was placed on the opposite side of the plate to insure symmetry of flow. A very clean joint was made between the obstacle and the glass so that any disturbance must have originated from the obstacle alone. The first obstacle used was a 1/4-inch round rod. Behind such a bluff body the wake represents, in the main, the energy dissipation of what is called form drag. This wake must be different in nature from the wake of a body having only what is called profile drag. A second obstacle was therefore used, this obstacle being a fine symmetrical airfoil set at zero angle of attack. The wake and the transition were measured for both obstacles. (See figs. 9 and 10.) The results from these obstacle tests convincingly support the hypothesis of lateral contamination. In both cases the transition spreads out from the center, once it is started by the wake of the obstacle, in precisely the same way that it spreads from the top and the bottom. It would be very difficult to attribute such a double-V transition region to any other cause.

In addition, surveys with the airfoil obstacle in place were made at two lower speeds. (See fig. 11.) In their general characteristics the transition regions for the three speeds are similar but the angle of diffusion decreases slowly with decreasing speed, confirming the previous results. The real physical significance of this dependence on speed must, however, await a more extensive investigation.

CONCLUSIONS

All the results lead to the conclusion that transition can be caused by a transverse contamination. In more precise terms, a mechanism exists by which boundary-layer transition can transport itself laterally across a surface. The phrase "transport itself" has the significance that the mechanism is self-sufficient and, once started, operates independently from the disturbance that started it and from the conditions in the external flow.

First, in all the wake and the transition surveys the spread of transition was much more rapid than the spread the motivating disturbance, in fact, the spread of the transition was governed by a different law. On the top and the bottom, the boundary-layer thicknesses increased according to a logarithmic law. Behind both the rod and the airfoil obstacles the wake thickness increased approximately as a narrow parabola. On the other hand, the transition region spread linearly with distance at a constant rate regardless of its originating cause. These differences can be explained only by an independently operating and self-sufficient mechanism governing the spread of transition.

Second, the lateral spread of transition can be explained satisfactorily by the familiar turbulent transport process. At transition the layers of the boundary flow close to the surface undergo a violent increase in velocity and an equally violent peak in turbulence. Such a combination of sharp velocity gradient and drastic turbulent agitation must surely generate and transport correlated vorticities of sufficient magnitude to upset completely the dynamic balance of the adjacent regions of the boundary layer that they contaminate. Thus; if transition starts at any point on the surface, it will contaminate its neighboring regions of the boundary layer, these in turn contaminate their neighboring regions, and so on across the surface; so that transition will spread from its source like a wave until it meets a solid boundary or a turbulent layer. Also, this spreading process is observed to take place at a constant rate, and such a linear behavior is most indicative of turbulent diffusion.

The comparatively rapid rate measured by a $9\frac{1}{2}^{\circ}$ angle of spread demands a word of explanation. On the assumption of a turbulent transport mechanism, this rate of diffusion requires roughly 17-percent turbulence, but just which particular layer of the boundary flow is responsible for the rate of spread is not established. The presence of velocity and turbulence gradients in all directions makes even a visualization of the case difficult. The result is probably the aggregate effect of many layers. The significant question at this stage in the investigation, however, is whether any layers exist with such an excessive magnitude of turbulence. The hot-wire surveys not only answered this question in the affirmative but also revealed layers possessing considerably more than the requisite 17-percent turbulence. It would seem that a $9\frac{1}{2}^{\circ}$ angle of spread is quite in accord with the hypothesis of transition by lateral contamination.

California Institute of Technology,
Pasadena, California, November 1939.

APPENDIX A

RECENT NOTES ON TRANSITION BETWEEN LAMINAR AND TURBULENT FLOW BY TRANSVERSE CONTAMINATION

By H. W. Liepmann

Recent measurements at the GALCIT have shown that the large fluctuations in the transition region of the boundary layer which have been observed in this paper as well as in reference 2 by Peters and by others indicate sudden changes in mean speed rather than turbulent fluctuations. To some extent this condition alters the aspect of the contamination effect, because these fluctuations cannot be assumed to be isotropic; in fact, the measurements show that the fluctuation components normal to the mean flow direction do not approach the values of 17 percent or more which were previously assumed.

It is believed that the contamination effect described in the main paper can be explained as a mixing rather than as a transport process in accordance with the following picture. Consider the boundary layer along a surface divided into two laterally contiguous regions in one of which the flow is laminar and in the other, turbulent. For purposes of visualization, the boundary between them might originally be considered as a plane perpendicular to the surface and parallel to the direction of mean flow. Because of the difference in shape between the laminar- and the turbulent-velocity profiles, the velocity in the fluid layers close to the surface will be higher in the turbulent than in the laminar boundary layer. In these layers then the phenomenon is essentially that of two adjacent, plane jets of fluid moving with different velocities. The mixing region between two such jets has been studied by Kuethe (see reference 3) and found to be wedge shape like the contamination region discussed herein. The experimentally found value for the angle of spread of contamination, $\tan \alpha = 0.17$, can be compared with the theoretical results of Kuethe for the mixing of two plane jets with velocities u_1 and u_2. According to Kuethe the limit of the mixing region is given by the expression

$$\tan \alpha = 0.0845 \times f(u_2/u_1)$$

where f is a certain function of the ratio u_2/u_1; and the constant is determined from Goettingen measurements. The experimentally found value, $\tan \alpha = 0.17$, requires $f \doteq 2$ or, according to Kuethe, $u_2/u_1 \doteq 0$. Hence, the angle of spread is compatible with the mixing theory if it is assumed that transition is caused mainly by the mixing of the layers very close to the wall where $u_2 \equiv u_{lam} << u_1 \equiv u_{turb}$. This assumption seems reasonable because the angle of spread is a maximum for $u_2/u_1 = 0$, and transition will probably occur along the outer edge of the mixing region.

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1. Clauser, Milton, and Clauser, Francis: The Effect of Curvature on the Transition from Laminar to Turbulent Boundary Layer. T.N. No. 613, NACA, 1937.

2. Peters, H.: A Study in Boundary Layers. Proc. Fifth Int. Cong. Appl. Mech. John Wiley & Sons, Inc., New York, 1939, pp. 393–395.

3. Kuethe, A. M.: Investigations of Turbulent Mixing Regions Formed by Jets. Jour. Appl. Mech., Vol. 2, No. 3, Sept. 1935, pp. 87–95.

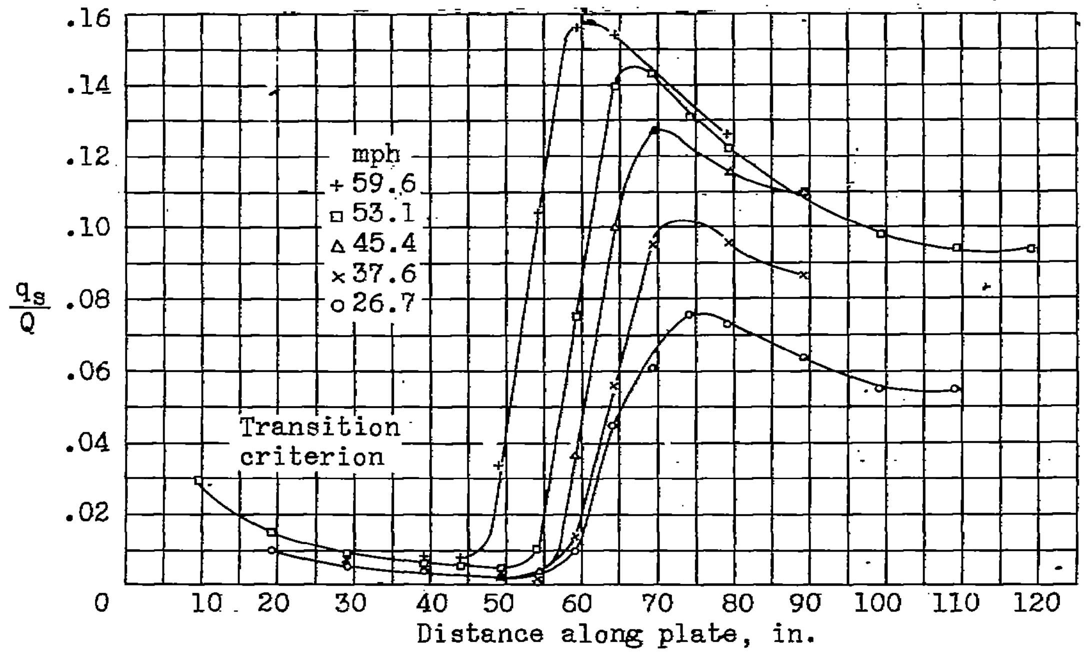


Figure 1.- Surface tube surveys along glass plate for a range of speeds. Stable pressure gradient. q_s = total pressure of surface tube, static pressure of free stream. Q = dynamic pressure of free stream.

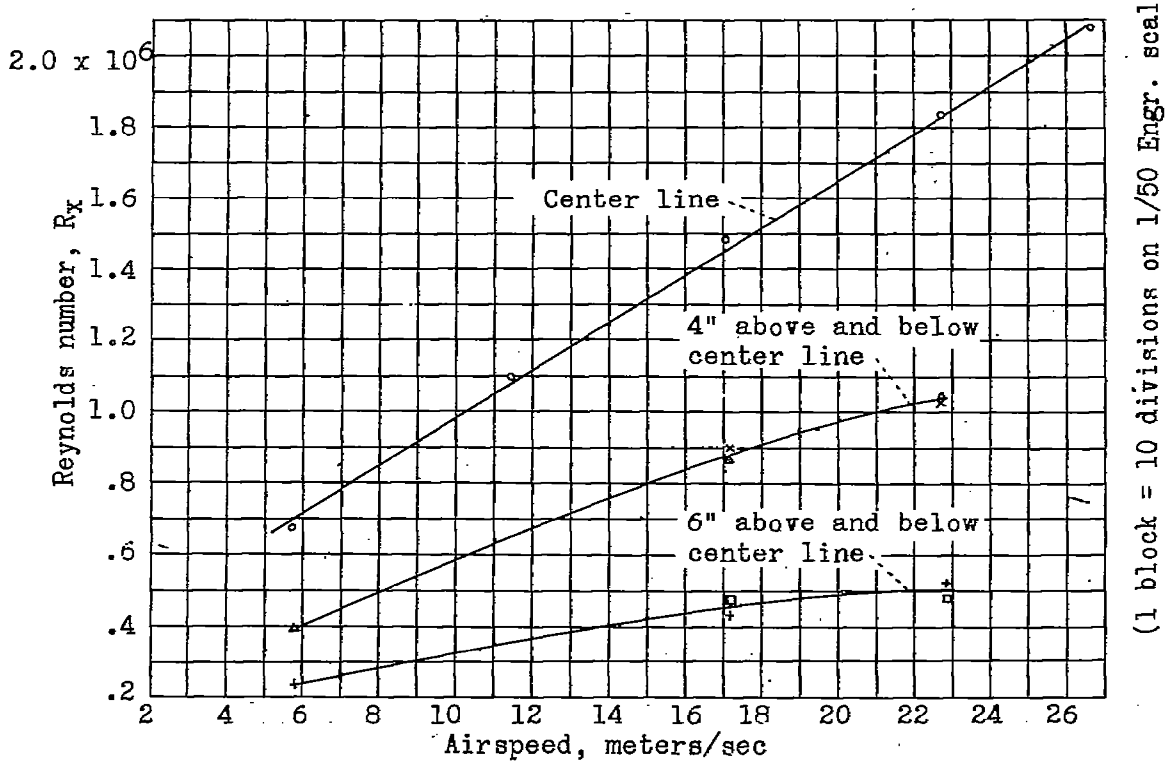


Figure 2.- Variation of Reynolds number of transition with speed for different positions on glass plate.

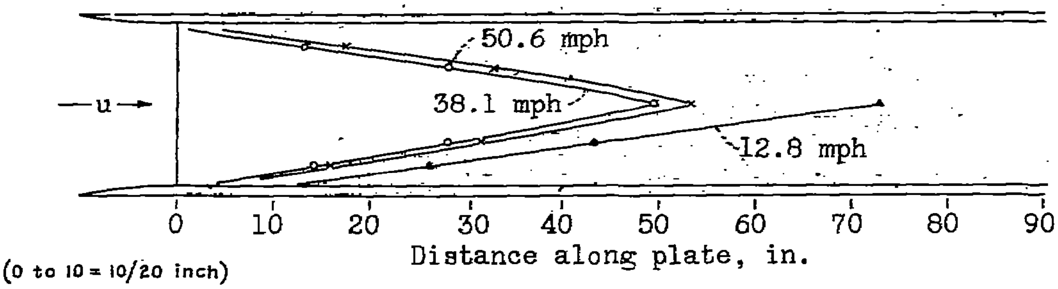
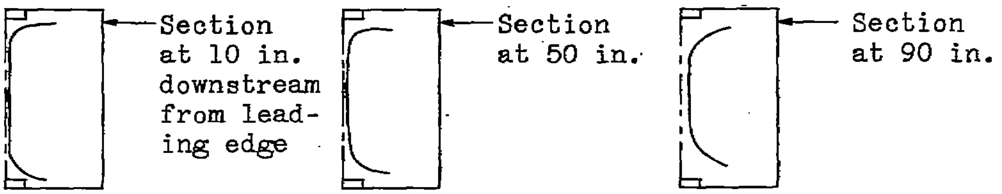
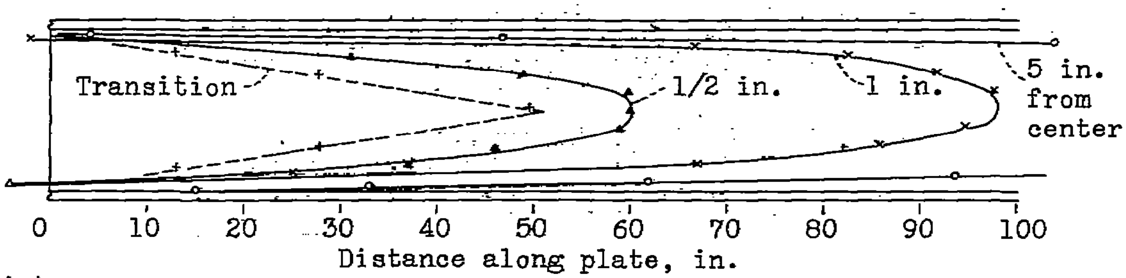


Figure 3.- Map of transition showing effect of speed. Neutral pressure gradient for 50.6 mph. Stable pressure gradient for 38.1 and 12.8 mph.



(a) Cross sections of half tunnel showing limit of boundary layer on top, bottom, and plate.



(b) Contour map showing boundary layer limit.

Figure 4.- Composite diagram showing surveys.

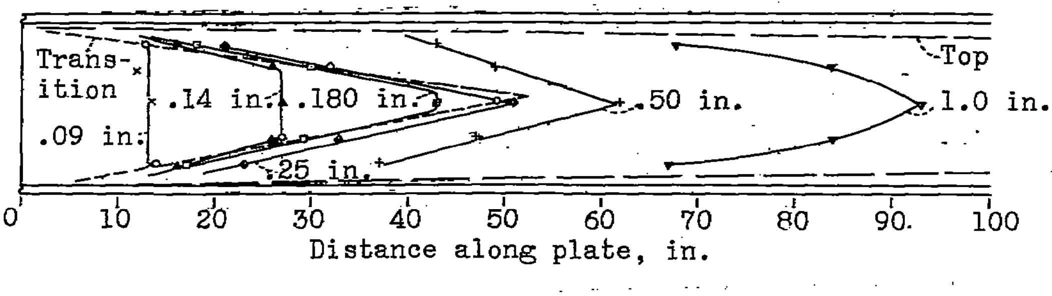


Figure 5.- Contour map showing limit of boundary layer on glass plate. Neutral pressure gradient; velocity = 51 mph; values of δ defined by $u/U = 0.995$.

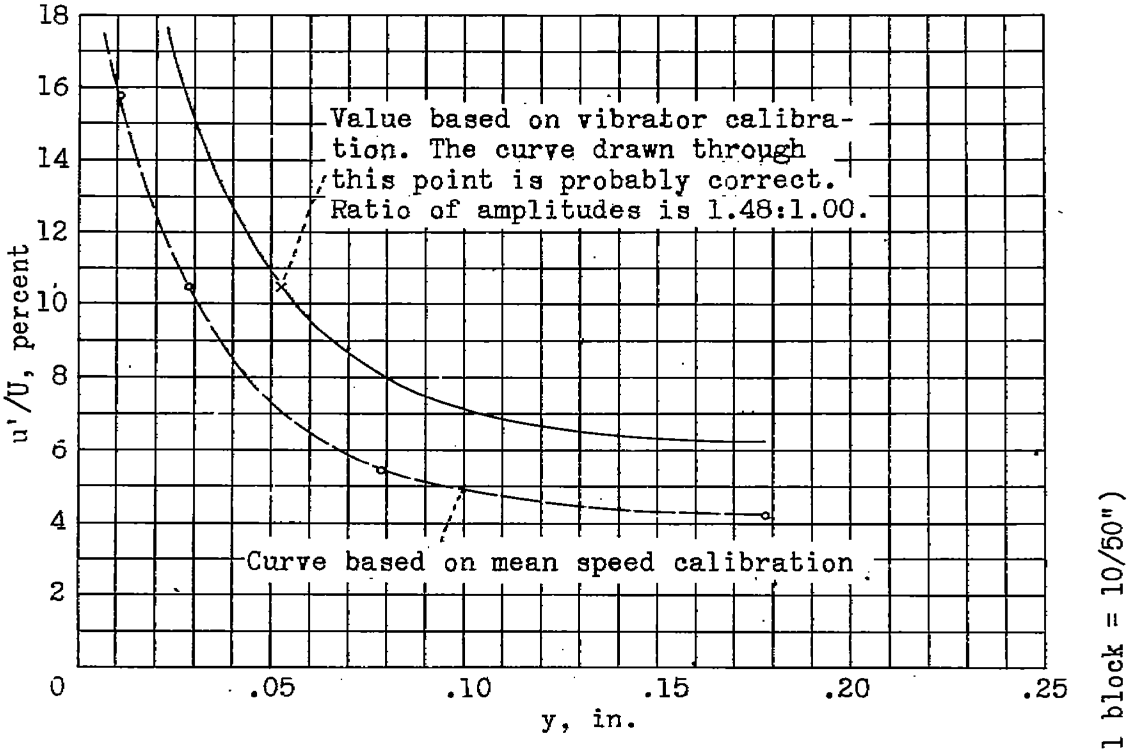


Figure 6.- Variation of maximum turbulence at transition with y based on survey along center line.

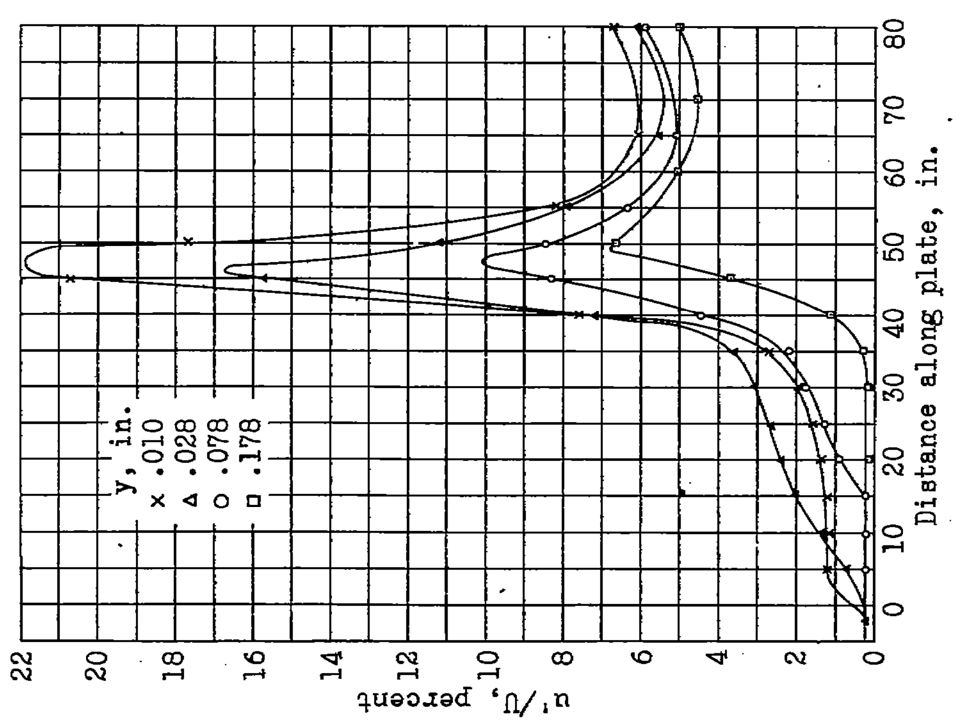


Figure 7.- Turbulence surveys along plate, 2 in. above center line for different distances from the surface.

Figure 8.- Map of transition showing effect of false top spaced at different distances from real top; velocity = 51 mph.

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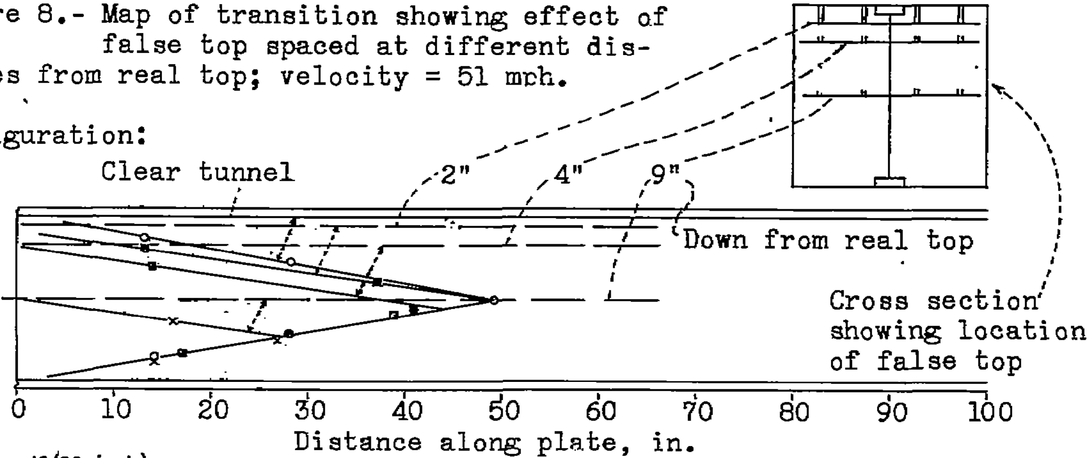

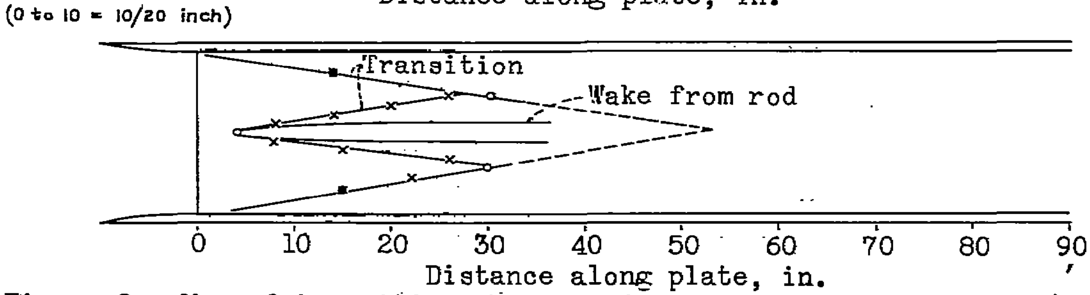

Figure 9.- Map of transition showing effect of blunt obstacle, 1/4" rod; velocity = 51 mph; neutral pressure gradient.

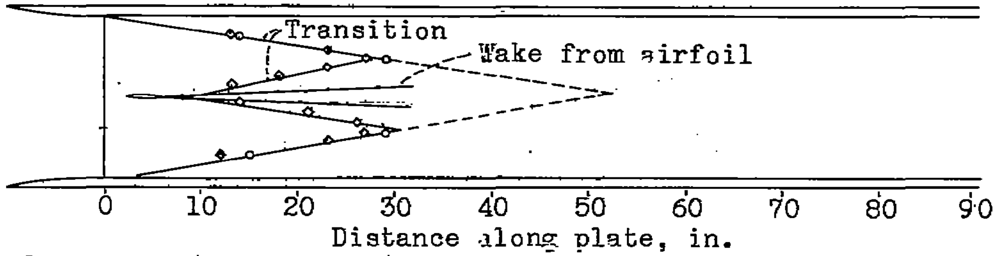

Figure 10.- Map of transition showing effect of streamline obstacle; double-arc 6 percent airfoil; velocity = 51 mph; neutral pressure gradient.

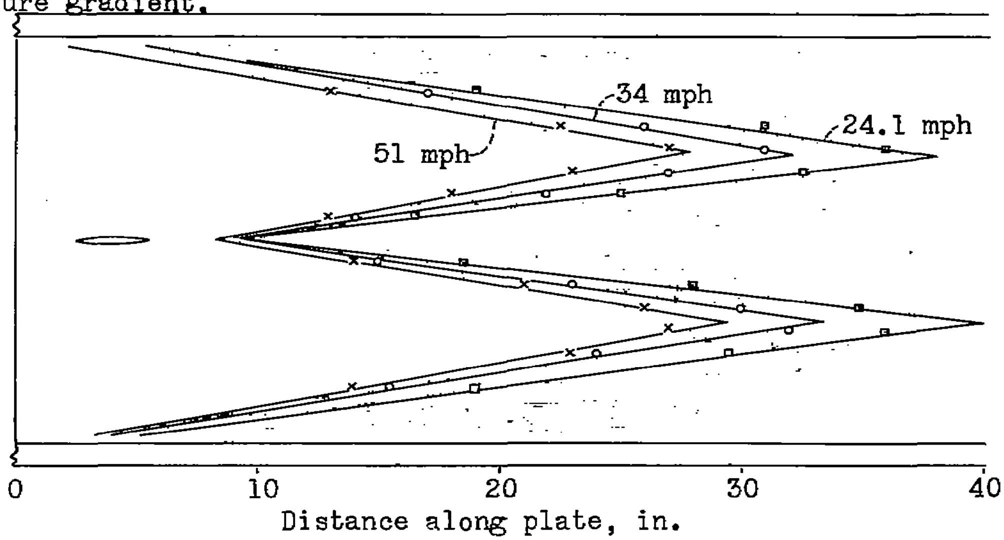

Figure 11.- Map of transition with streamline obstacle in place showing effect of speed.